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THE ISOTOPIC COMPOSITION OF HYDROGEN AND HELIUM IN LOW ENERGY COSMIC RAYS

R. A. Mewaldt, E. C. Stone, and R. E. Vogt

California Institute of Technology
Pasadena, California 91125

The Caltech Electron/Isotope Spectrometer on IMP-7 has been used to identify the isotopes ^2H and ^3He in low energy cosmic rays during solar quiet periods from October 1972 to October 1974. These observations cover the energy intervals 5 - 29 MeV/nuc for ^2H and 7 - 50 MeV/nuc for ^3He. The energy spectra of ^1H, ^2H and ^3He all fall rapidly with decreasing energy, giving $^2H/^1H$ and $^3He/^1H$ ratios essentially independent of energy as expected from adiabatic acceleration. The measured ^4He spectrum, however, was essentially flat over this energy interval, and therefore the $^2H/^4He$ ratio observed at 1 AU is not simply related to the interstellar abundances of these nuclei. However, comparisons of the $^2H/^1H$ and $^3He/^1H$ ratios with calculated spectra are possible.

1. Introduction. The rare isotopes ^2H and ^3He in cosmic rays are generally believed to be of secondary origin, resulting mainly from the nuclear interaction of primary cosmic ray protons and ^4He with the interstellar medium. It is therefore expected that the relative abundance of the H and He isotopes will reflect the mean pathlength of cosmic ray ^1H and ^4He in the interstellar medium, the energy spectra of these nuclei, and the energy dependence of the relevant nuclear interaction cross sections.

Satellite measurements of ^2H and ^3He in the years prior to 1972 have been summarized by Baity et al. (1971). Observations of hydrogen and helium isotopes in and since 1972 have found $^2H/^4He$ ratios significantly lower than in earlier years (Teegarden et al., 1973; Hurford et al., 1973; Anglin et al., 1974), due mainly to an enhanced low energy ^4He flux (Garcia Munoz et al., 1973; Van Hollebeke et al., 1973).

In this paper we report 1973-4 measurements of the H and He isotopes between ~ 5 and 50 MeV/nucleon and compare these observations with the results of interstellar propagation and solar modulation calculations.

2. Observations. The observations reported here were made with the Caltech Electron/Isotope Spectrometer (EIS) which was launched on the IMP-7 spacecraft in September 1972. The detector system, which consists of a stack of 11 fully depleted silicon surface barrier detectors with anticoincidence shielding, has been described by Hurford et al. (1974). Hydrogen and helium event data were summed over specific time intervals during the periods Dec. 28, 1972 to Oct. 1, 1973 and Nov. 16, 1973 to Oct. 22, 1974. For the ^2H and ^3He measurements, periods during which the flux of 4-10 MeV protons was greater than 0.15 cm^{-2} sec^{-1} sr^{-1} were excluded, thereby eliminating large solar flares, but not small events. Small "^3He rich" solar flares (Hurford et al., 1975) were identified

and eliminated by analyzing the isotopic composition of 3-15 MeV/nuc He nuclei on a day by day basis. Examination of the spectra and counting rates during the remaining 510 days showed no evidence for solar ^{2}H or ^{3}He contamination at energies > 5 MeV/nuc. In order to minimize the solar contamination of ^{1}H, the ^{1}H and ^{4}He spectra were obtained over a more restricted sample of 25 days distributed over this 2 year period, when the flux of 1.3-2.3 MeV protons was < 5×10^{-3} cm^{-2} ster^{-1} sec^{-1}. The flux of ~ 30 MeV protons during the 25 day sample was within $\leq$ 10% of the flux at that energy averaged over the 510 day period. This suggests that the 25 day ^{1}H spectrum is indicative of the lower energy galactic ^{1}H flux over the entire 510 day period.

Hydrogen and helium isotope identification was accomplished by the dE/dx-E-range technique (Hurford et al.,1973). Examples of the hydrogen and helium mass spectra obtained are shown in *Figures 1 and 2*. At energies ≥ 20 MeV/nuc the ^{2}H peaks (*Figures 1A and 1B*) are clearly resolved and well separated from the ^{1}H peaks, with signal/noise ratios better than earlier experiments in this energy range. The background level is somewhat higher for 13-19 MeV/nuc ^{2}H (*Figure 1C*) and for the ^{3}He data at ≥ 35 MeV/nuc (*Figures 2A and 2B*). The inset in *Figure 1C* shows the result of subtracting the background in the 13-19 MeV/nuc ^{2}H region,

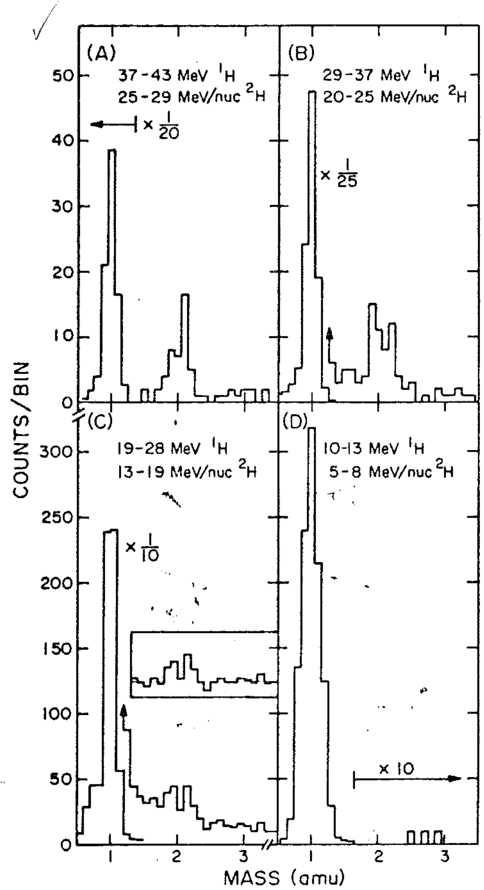


Fig. 1. Hydrogen mass spectra. Note the use of scale factors for the ^{1}H peaks. See text for discussion of Figure 1C inset.

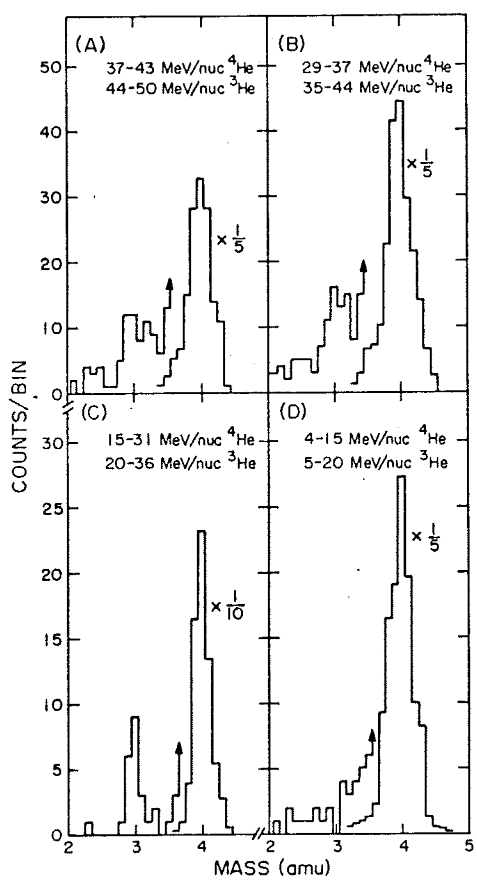


Fig. 2. Helium mass spectra. Note the use of scale factors for the ^{4}He peaks.

as determined from a simultaneous least squares fit to ^{1}H and ^{2}H peaks and to the background. At the lowest energies the relative ^{2}H (*Figure 1D*) and ^{3}He (*Figure 2D*) abundances are much smaller, and only upper limits to their intensity can be obtained. Note that differences in the background levels and absolute counting rates in the various energy intervals shown in *Figures 1 and 2* result from differences in the geometry factors and background rejection capabilities of the various instrumental analysis modes (see Hurford et al., 1973, 1974).

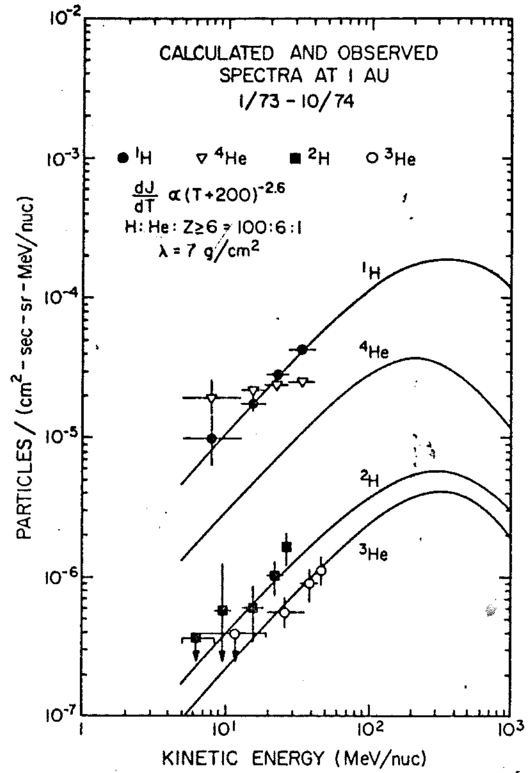


Fig. 3. Calculated and observed H and He isotope spectra at 1 AU.

3. Results. The quiet time energy spectra obtained for hydrogen and helium isotopes are shown in *Figure 3*. Notice in particular that while the ^{1}H, ^{2}H and ^{3}He spectra are approximately proportional to kinetic energy, the ^{4}He intensity is to first approximation independent of energy, and from ~ 5 to ~ 20 MeV/nuc ^{4}He exceeds ^{1}H in abundance. This relatively flat ^{4}He spectrum, first observed in 1972 (Garcia-Munoz et al., 1973; Van Hollebeke et al., 1973), was a stable feature over the time interval covered by these observations.

Over the regions of overlap, the energy dependence of the spectra reported here are consistent with 1972 ^{2}H and ^{4}He observations (Teegarden et al., 1973; see also Stone, 1973) and 1973-74 ^{1}H, ^{3}He, and ^{4}He observations (Garcia-Munoz et al., 1975). Differences in absolute intensity between the observations made since late 1972 appear to result mainly from changes in the level of solar modulation between the different times of measurement. Over the period covered by this study we have observed quiet time variations of a factor of ~ 2 in absolute intensity, with no significant changes in the spectral shapes shown in *Figure 3*.

4. Calculated Spectra at 1 AU. In order to interpret the observations reported here we have performed interstellar propagation and solar modulation calculations for a cosmic ray source composed of ^{1}H, ^{4}He and $Z \geq 6$ nuclei, and identical source spectra of the form $\frac{dJ}{dT} \propto (T+E_0)^{-2.6}$ where T is the kinetic energy/nuc, and E_0 varied from 938 MeV/nuc (total energy power law) to 0 (kinetic energy power law). We assumed an exponential pathlength distribution with mean pathlength λ for cosmic rays in an interstellar medium with He/H = 0.1, and used the cross sections for ^{2}H and ^{3}He production summarized by Meyer (1974). Ionization energy-loss and nuclear reaction kinematics effects were included. The resulting equilibrium interstellar spectra were consistent with those of Meyer (1974)

when identical initial parameters were used; however, we found it necessary to use somewhat different source abundances in order to achieve agreement of the modulated high energy ^{4}He and $Z \geq 6$ spectra with measurements at 1 AU.

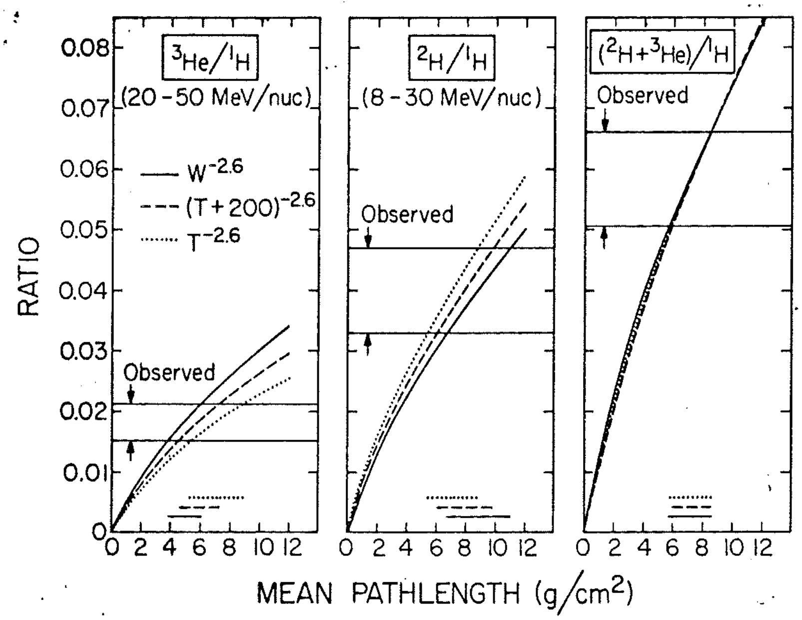
In our solar modulation calculations we used the numerical techniques of Fisk (1971) to solve the full Fokker-Planck equation, including the effects of diffusion, convection, and adiabatic deceleration, and used the solar minimum (1965-6) modulation parameters determined by Cummings et al. (1973a) from a study of the solar modulation of electrons and positrons. The modulation parameters were allowed to vary within the limits set by the uncertainty in the determination of the galactic non-thermal radio emission (Cummings et al., 1973b). *Figure 3* shows fits to the observations at 1 AU for one choice of possible source spectra, $dJ/dT \propto (T + 200)^{-2.6}$, similar to a power law in rigidity. The only parameters adjusted in order to achieve this fit were a constant factor multiplying the diffusion coefficient, the mean pathlength λ, and the source abundances of ^{4}He and $Z \geq 6$ nuclei, which were adjusted to fit observations in the 100-300 MeV/nuc interval, as summarized by Webber and Lezniak (1974). Notice that we obtain very reasonable fits to the ^{1}H, ^{2}H and ^{3}He spectra, but fall far below the low energy ^{4}He observations.

5. Discussion. It can be seen in *Figure 3* that the calculated spectra at 1 AU are approximately proportional to kinetic energy below ~ 100 MeV/nuc. This $J \simeq AT$ behavior is characteristic of the predictions of current theories of the solar modulation of galactic cosmic rays, in which the modulation of low energy particles is dominated by adiabatic deceleration (see e.g. Goldstein et al. 1970). In this case low energy particles observed at 1 AU had energies of several hundred MeV/nuc in interstellar space, and we expect the abundance ratios observed at 1 AU to be independent of energy. From a comparison of the observed spectra with our calculated interstellar spectra (see also Meyer, 1974), we conclude that adiabatic deceleration does dominate the modulation of ^{1}H, ^{2}H and ^{3}He, while the 1972-4 ^{4}He observations are inconsistent with this picture. Because of the uncertain origin of the enhanced ^{4}He flux we will focus our attention on the ^{1}H, ^{2}H, and ^{3}He spectra.

In *Figure 4* we show the dependence of the calculated ^{2}H/^{1}H and (^{3}He/^{1}H) ratios as a function of the mean pathlength λ, for three characteristic spectral shapes. Also shown are the 68% confidence intervals based on our observations. Note that our ^{2}H/^{1}H observations imply somewhat longer but not inconsistent values for λ than the ^{3}He/^{1}H observations. Possibly the best estimate for λ comes from the (^{2}H+^{3}He)/^{1}H ratio, which for all three spectra is ~ 7 ± 2 g/cm^2. This pathlength is consistent with that required by other nuclear species of secondary origin, including Li, Be, and B, and the products of Fe fragmentation (see e.g., Shapiro et al., 1973). Inspection of *Figure 4* shows that the abundance ratios at 1 AU are relatively insensitive to the source spectra, mainly because the largest interstellar spectral differences occur at low energies, where adiabatic deceleration dominates. Although the ^{2}H/^{3}He ratio, which is to first approximation independent of λ, might discriminate between possible source spectra, our observed ^{2}H/^{3}He ratio is compatible with all spectra considered here.

Meyer (1974) and Ramadurai and Biswas (1974) have recently concluded that only source spectra similar to power laws in total energy/nucleon were consistent

Fig. 4. Calculated dependence of isotopic abundance ratios at 1 AU on the mean interstellar pathlength λ for 3 characteristic source spectra.



with earlier observations. However, that analysis was based on the low energy $^2H/^4He$ and $^3He/^4He$ ratios, which, because of the uncertain origin of the low energy ^4He, are difficult to relate to the interstellar abundances of these isotopes.

In summary, the ^1H, ^2H and ^3He spectra that we observe can be fit with models of interstellar propagation and solar modulation parameters designed to explain other cosmic ray species. On the other hand the low energy ^4He spectrum observed since 1972 is not easily explained by this picture, suggesting that the local interstellar ^4He and ^1H spectra differ markedly, or that there is an additional source of ^4He of local origin (Hurford et al., 1973). A similar conclusion has been reached by Garcia-Munoz et al. (1975), based on a study of the ^3He, ^4He and B spectra.

Secondly, we conclude that present low energy measurements of ^2H and ^3He at earth do not provide sensitive tests of the interstellar cosmic ray spectra.

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7. References.

Anglin, J. D., J. A. Simpson, and R. Zamow, "The Abundances of D and He^3 in the Galactic Cosmic Rays", Bull. Am. Phys. Soc., 19, 67, 1974.

Baity, W. H., B. Teegarden, J. A. Lezniak, and W. R. Webber, "Intensities of Low Energy Cosmic Ray ^2H and ^3He Nuclei Measured in 1967-8", Astrophys. J., 164, 521, 1971.

Cummings, A. C., E. C. Stone, and R. E. Vogt, "Evidence for Primary Interstellar Cosmic Ray Electrons", 13th Int. Cosmic Ray Conf., Conf. Papers, Denver, 1, 340, 1973a.

Cummings, A. C., E. C. Stone, and R. E. Vogt, "Interstellar Electron Spectrum from the Galactic Non-Thermal Radio Emission", 13th Int. Cosmic Ray Conf., Conf. Papers, Denver, 1, 335, 1973b.

Fisk, L. A., "Solar Modulation of Galactic Cosmic Rays, 2", J. Geophys. Res., 76, 221, 1971.

Garcia-Munoz, M., G. M. Mason, and J. A. Simpson, "A New Test for Solar Modulation Theory: The 1972 May-July Low-Energy Galactic Cosmic Ray Proton and Helium Spectra", Astrophys. J., 182, L81, 1973.

Garcia-Munoz, M., G. M. Mason, and J. A. Simpson, "The Anomalous ^{4}He Component in the Cosmic Ray Spectrum at $\leqslant$ 50 MeV Per Nucleon During 1972-1974", to be published in Astrophys. J., 1975.

Goldstein, M. L., L. A. Fisk, and R. Ramaty, "Energy Loss of Cosmic Rays in the Interplanetary Medium", Phys. Rev. Letters, 25, 832, 1970.

Hurford, G. J., "Observations of Low Energy Hydrogen and Helium Isotopes During Solar Quiet Times", 13th Int. Cosmic Ray Conf., Conf. Papers, Denver, 1, 93, 1973.

Hurford, G. J., R. A. Mewaldt, E. C. Stone, and R. E. Vogt, "The Energy Spectrum of 0.16 to 2 MeV Electrons During Solar Quiet Times", Astrophys. J., 192, 541, 1974.

Hurford, G. J., E. C. Stone, and R. E. Vogt, "Observations of Hydrogen and Helium Isotopes in Solar Cosmic Rays", Proc. 14th Int. Cosmic Ray Conf., Munich, Paper SP 2.1-16, 1975.

Mewaldt, R. A., E. C. Stone, S. B. Vidor, and R. E. Vogt, "Isotopic Composition of the Anomalous Low Energy Cosmic Ray Nitrogen and Oxygen", Proc. 14th Int. Cosmic Ray Conf., Munich, Paper OG 7-10, 1975.

Meyer, J. P., "Creation de Deuterons et d'He^3 au cours de la Propagation Interstellaire du Rayonnement Cosmique", Ph.D. Thesis, Univ. of Paris (Orsay), 1974.

Ramadurai, S., and S. Biswas, "Production and Propagation of Cosmic Ray H^2 and He^3 Nuclei", Astrophys. Space Sci., 30, 181, 1974.

Shapiro, M. M., R. Silberberg, and C. H. Tsao, "Relative Abundances of Cosmic Ray Nuclei at the Sources", 13th Int. Cosmic Ray Conf., Conf. Papers, Denver, 1, 99, 1973.

Stone, E. C., "Cosmic Ray Isotopes", 13th Int. Cosmic Ray Conf., Conf. Papers, Denver, 5, 3615, 1973.

Teegarden, B. J., T. T. von Rosenvinge, and F. B. McDonald, "Improved Measurements of the Isotopes of Cosmic Ray Hydrogen and Helium", *ibid*, 1, 99, 1973.

Van Hollebeke, M. A. I., J. R. Wang, and F. B. McDonald, "The Modulation of Low Energy Galactic Cosmic Rays", *ibid*, 2, 1298, 1973.

Webber, W. R. and Lezniak, J. A., "The Comparitive Spectra of Cosmic-Ray Protons and Helium Nuclei", Astrophys. Space Sci., 30, 361, 1974.